# Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

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# Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

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## Abstract

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within $\pm 500$ s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation mechanisms in relativistic outflows driven by the binary neutron star merger. The non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle.

*Key words:* gamma-ray burst: general – gravitational waves – neutrinos

## 1. Introduction

The observation of binary neutron star mergers with multiple cosmic messengers is a unique opportunity that enables the detailed study of the merger process and provides insight into astrophysical particle acceleration and high-energy emission (e.g., Faber & Rasio 2012; Bartos et al. 2013; Berger 2014; Abbott et al. 2017a). Binary neutron star mergers are prime sources of gravitational waves (GWs; e.g., Abadie et al. 2010), which provide information on the neutron star masses and spins (e.g., Veitch et al. 2015). Kilonova/macronova observations of the mergers provide further information on the mass ejected by the disruption of the neutron stars (e.g., B. Abbott et al. 2017, in preparation; Metzger 2017).

Particle acceleration and high-energy emission by compact objects are currently not well understood (e.g., Mészáros 2013; Kumar & Zhang 2015) and could be deciphered by combined information on the neutron star masses, ejecta mass, and gamma-ray burst (GRB) properties, as expected from multi-messenger observations. In particular, the observation of high-energy neutrinos would reveal the hadronic content and dissipation mechanism in relativistic outflows (Waxman & Bahcall 1997). A quasi-diffuse flux of high-energy neutrinos of cosmic origin has been identified by the IceCube observatory (Aartsen et al. 2013a, 2013b). The source population producing these neutrinos is currently not known.

On 2017 August 17, the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) observatories recorded a GW signal, GW170817, from a binary neutron star inspiral (Abbott et al. 2017b). Soon afterward, *Fermi*-GBM and *INTEGRAL* detected a short GRB, GRB 170817A, from a consistent location (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017). Subsequently, ultraviolet, optical, and infrared emission was observed from the merger, consistent with kilonova/macronova emission. Optical observations allowed the precise localization of the merger in the galaxy NGC 4993, at equatorial coordinates $\alpha(\mathrm{J2000.0}) = 13^{\mathrm{h}}09^{\mathrm{m}}48\overset{\mathrm{s}}{.}085$, $\delta(\mathrm{J2000.0}) = -23°22'53\overset{''}{.}343$ (Abbott et al. 2017c; Coulter et al. 2017a, 2017b), and at a distance of $\sim$40 Mpc. At later times, X-ray and radio emissions were also observed (Abbott et al. 2017c), consistent with the expected afterglow of a short GRB at high viewing angles (e.g., Abbott et al. 2017a).

High-energy neutrino observatories continuously monitor the whole sky or a large fraction of it, making them well suited for studying emission from GW sources, even for unknown source locations or for emission prior to or after the GW detection (Adrián-Martínez et al. 2016a; Albert et al. 2017a). It is also possible to rapidly analyze the recorded data and inform other observatories in the case of a coincident detection, significantly reducing the source localization uncertainty compared to that provided by GW information alone.

In this Letter, we present searches for high-energy neutrinos in coincidence with GW170817/GRB 170817A by the three most sensitive high-energy neutrino observatories: (1) the ANTARES neutrino telescope (hereafter ANTARES; Ageron et al. 2011), a 10 megaton-scale underwater Cherenkov neutrino detector located at a depth of 2500 m in the Mediterranean Sea; (2) the IceCube Neutrino Observatory (hereafter IceCube; Aartsen et al. 2017), a gigaton-scale neutrino detector installed 1500 m deep in the ice at the geographic South Pole, Antarctica; and (3) the Pierre Auger Observatory (hereafter Auger; Aab et al. 2015b), a cosmic-ray air-shower detector consisting of 1660 water-Cherenkov stations spread over an area of $\sim$3000 km$^2$. All three detectors joined the low-latency multi-messenger follow-up effort of LIGO–Virgo starting with LIGO's second observation run, O2.

Upon the identification of the GW signal GW170817, preliminary information on this event was rapidly shared with partner observatories (Abbott et al. 2017c). In response, IceCube (Bartos et al. 2017a, 2017b, 2017c), ANTARES (Ageron et al. 2017a, 2017b), and Auger (Alvarez-Muniz et al. 2017) promptly searched for a neutrino counterpart and shared their initial results with partner observatories. Subsequently, the three facilities carried out a more in-depth search for a neutrino counterpart using the precise localization of the source.

This Letter is organized as follows. In Section 2, we present the neutrino searches carried out by ANTARES, IceCube, and Auger, as well as the results obtained. In Section 3, we present constraints on processes in the merger that can lead to neutrino emission. We summarize our findings and conclude in Section 4.

## 2. Searches and Results

Neutrino observatories detect secondary charged particles produced in neutrino interaction with matter. Surface detectors, such as Auger, use arrays of widely spaced water-Cherenkov detectors to observe the air-shower particles created by high-energy neutrinos. In detectors such as ANTARES and IceCube, three-dimensional arrays of optical modules deployed in water or ice detect the Cherenkov radiation from secondary charged particles that travel through the instrumented detector region. For these detectors, the secondary particles can create two main event classes: track-like events from charged-current interactions of muon neutrinos and from a minority of tau neutrino interactions and shower-like events from all other interactions (neutral-current interactions and charged-current interactions of electron and tau neutrinos). While energy deposition in track-like events can happen over distances of $\mathcal{O}$(km), shower-like events are confined to much smaller regions.

For all detectors, neutrino signals must be identified on top of a persistent background of charged particles produced by the interaction of cosmic-ray particles with the atmosphere above the detectors. This discrimination is done by considering the observed direction and energy of the charged particles. Surface detectors focus on high-energy ($\gtrsim 10^{17}$eV) showers created close to the detector by neutrinos from near-horizontal directions. In-ice and in-water detectors can select well-reconstructed track events from the up-going direction where the Earth is used as a natural shield for the dominant background of penetrating muons from cosmic-ray showers. By requiring the neutrino interaction vertex to be contained inside the instrumented volume, or requiring its energy to be sufficiently high to be incompatible with the down-going muon background, even neutrino events originating above the horizon are identifiable. Neutrinos originating from cosmic-ray interactions in the atmosphere are also observed and constitute the primary background for up-going and vertex-contained event selections.

All three observatories, ANTARES, IceCube, and Auger, performed searches for neutrino signals in coincidence with the binary neutron star merger event GW170817, each using multiple event selections. Two different time windows were used for the searches. First, we used a $\pm 500$ s time window around the merger to search for neutrinos associated with prompt and extended gamma-ray emission (Baret et al. 2011; Kimura et al. 2017). Second, we searched for neutrinos over a longer 14 day time window following the GW detection, to cover predictions of longer-lived emission processes (e.g., Gao et al. 2013; Fang & Metzger 2017).

### 2.1. ANTARES

The ANTARES neutrino telescope has been continuously operating since 2008. Located deep (2500 m) in the Mediterranean Sea, 40 km from Toulon (France), it is a 10 Mt-scale array of photosensors, detecting neutrinos with energies above $\mathcal{O}(100)$ GeV.

Based on the originally communicated locations of the GW signal and the GRB detection, high-energy neutrino candidates were initially searched for in the ANTARES online data stream, relying on a fast algorithm that selects only up-going neutrino track candidates (Adrián-Martínez et al. 2016b). No up-going muon neutrino candidate events were found in a $\pm 500$ s time window centered on the GW event time—for an expected number of atmospheric background events of $\sim 10^{-2}$ during the coincident time window. An extended online search during $\pm 1$ hr also resulted in no up-going neutrino coincidences.

As it subsequently became clear, the precise direction of origin of GW170817 in NGC 4993 was above the ANTARES horizon at the detection time of the binary merger (see Figure 1). Thus, a dedicated analysis looking for down-going muon neutrino candidates in the online ANTARES data stream was also performed. No neutrino counterparts were found in this analysis. The results of these low-latency searches were shared with follow-up partners within a few hours for the up-going search and a few days for the down-going search (Ageron et al. 2017a, 2017b).

Here, ANTARES used an updated high-energy neutrino follow-up of GW170817 that includes the shower channel. It was performed with the offline-reconstructed data set that incorporates dedicated calibration in terms of positioning, timing, and efficiency (Aguilar et al. 2011, 2007; Adrián-Martínez et al. 2012). The analysis has been optimized to increase the sensitivity of the detector and extended to the longer time window of 14 days.

The search for down-going neutrino counterparts to GW170817 was made feasible as the large background affecting this data set can be drastically suppressed by requiring a time and space coincidence with the GW signal. It was optimized, independently for tracks and showers, such that a directional coincidence with NGC 4993 within the search time window of $\pm 500$ s would have $3\sigma$ significance. Muon neutrino candidates were selected by applying cuts on the estimated angular error and the track quality reconstruction parameter. While ANTARES is sensitive to neutrino events with energy as small as $\mathcal{O}$(100 GeV), the energy range corresponding to the 5%–95% quantiles of the neutrino flux for an $E^{-2}$ signal spectrum is equal to [32 TeV; 22 PeV]. For such a flux, the median angular uncertainty, defined as the median value of the distribution of angles between the reconstructed direction of the event and the true neutrino direction, is equal to $0\overset{\circ}{.}5$.

Shower events were selected by applying a set of cuts primarily devoted to reducing the background rate (Albert et al. 2017b). The energy range corresponding to the 5%–95% quantiles of the neutrino flux for an $E^{-2}$ signal spectrum is equal to [23 TeV; 16 PeV], while the median angular error is $6^\circ$ with this set of relaxed cuts.

No events temporally coincident with GW170817 were found. Five background track events (likely atmospheric muons), not compatible with the source position, were detected

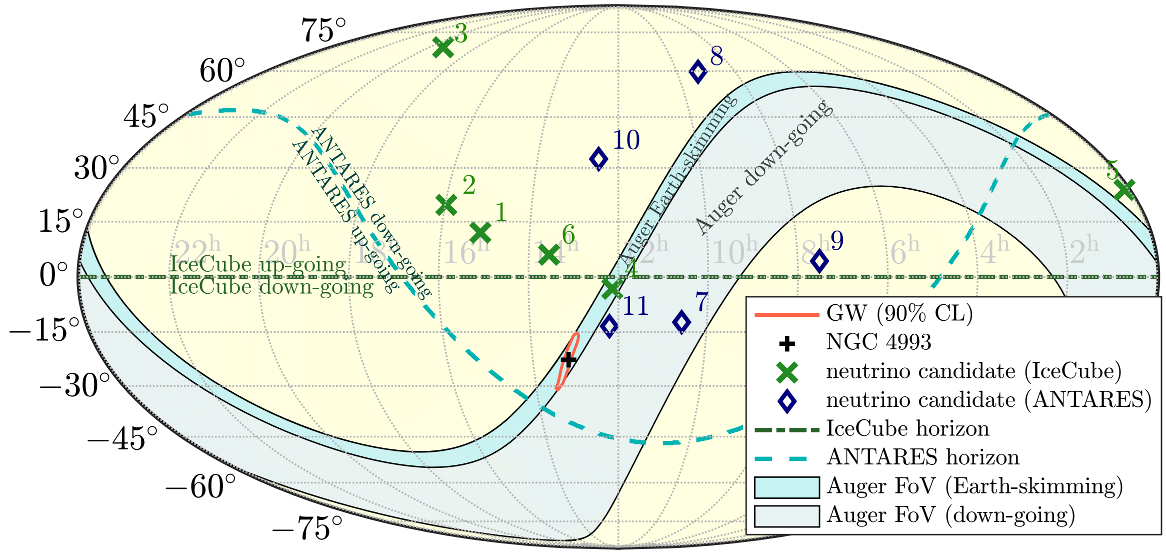


**Figure 1.** Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017b), direction of NGC 4993 (black plus symbol; Coulter et al. 2017b), directions of IceCube's and ANTARES's neutrino candidates within 500 s of the merger (green crosses and blue diamonds, respectively), ANTARES's horizon separating down-going (north of horizon) and up-going (south of horizon) neutrino directions (dashed blue line), and Auger's fields of view for Earth-skimming (darker blue) and down-going (lighter blue) directions. IceCube's up-going and down-going directions are on the northern and southern hemispheres, respectively. The zenith angle of the source at the detection time of the merger was 73°.8 for ANTARES, 66°.6 for IceCube, and 91°.9 for Auger.

(see Figure 1). We used this non-detection to constrain the neutrino fluence (see Figure 2) that was computed as in Adrián-Martínez et al. (2016a).

The search over 14 days is restricted to up-going events, but includes all neutrino flavors (tracks and showers). We applied quality cuts optimized for point-source searches that give a median pointing accuracy of 0°.4 and 3°, respectively, for track and shower events (Albert et al. 2017b). No events spatially coincident with GRB 170817A were found.

Compared to the upper limits obtained for the short time window of ±500 s, those limits are significantly less stringent above 1 PeV, where the absorption of neutrinos by the Earth becomes important for up-going events. Below 10 TeV, the constraints computed for the 14 day time window are stricter due to the better acceptance in this energy range for up-going neutrino candidates compared to down-going events (see Figure 2).

### 2.2. *IceCube*

IceCube is a cubic-kilometer-size neutrino detector (Aartsen et al. 2017) installed in the ice at the geographic South Pole in Antarctica between depths of 1450 m and 2450 m. Detector construction was completed in 2010, and the detector has operated with a ~99% duty cycle since. IceCube searched for neutrino signals from GW170817 using two different event selection techniques.

The first search used an online selection of through-going muons, which is used in IceCube's online analyses (Aartsen et al. 2016; Kintscher & The IceCube Collaboration 2016) and follows an event selection similar to that of point source searches (Aartsen et al. 2014a). This event selection picks out primarily cosmic-ray-induced background events, with an expectation of 4.0 events in the northern sky (predominantly generated by atmospheric neutrinos) and 2.7 events in the southern sky (predominantly muons generated by high-energy cosmic rays interactions in the atmosphere above the detector) per 1000 s. For source locations in the southern sky, the sensitivity of the down-going event selection for neutrinos below 1 PeV weakens rapidly with energy due to the rapidly increasing atmospheric muon background at lower energies. Events found by this track selection in the ±500 s time window are shown in Figure 1. No events were found to be spatially and temporally correlated with GW170817.

A second event selection, described in Wandkowski et al. (2017), was employed offline. This uses the outermost optical sensors of the instrumented volume to veto incoming muon tracks from atmospheric background events. Above 60 TeV, this event selection has the same performance as the high-energy starting-event selection (Aartsen et al. 2014b). Below this energy, additional veto cuts similar to those described in Aartsen et al. (2015) are applied, in order to maintain a low background level at energies down to a few TeV. Both track- and cascade-like events are retained. The event rate for this selection varies over the sky, but is overall much lower than for the online track selection described above. Between declinations −13° and −33°, the mean number of events in a two-week period is 0.4 for tracks and 2.5 for cascades. During the ±500 s time window, no events passed this event selection from anywhere in the sky.

A combined analysis of the IceCube through-going track selection and the starting-event selection allows upper limits to be placed on the neutrino fluence from GW170817 between the energies of 1 TeV and 1 EeV, as shown in Figure 2. In the central range from 10 TeV to 100 PeV, the upper limit for an $E^{-2}$ power-law spectral fluence is $F(E) = 0.19(E/\mathrm{GeV})^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}$.

Both the through-going track selection and the starting-event selection were applied to data collected in the 14 day period following the time of GW170817. Because of IceCube's location at the South Pole and 99.88% on-time during the 14 day period, the exposure to the source location is continuous and unvaried. No spatially and temporally coincident events were seen in either selection during this follow-up period. The resulting upper limits are presented in Figure 2. At most energies these are unchanged from the short time window. At the lowest energies, where most background events occur, the analysis effectively requires stricter criteria for a coincident event than were required in the short time window; the limits are correspondingly higher. In the central range from 10 TeV to

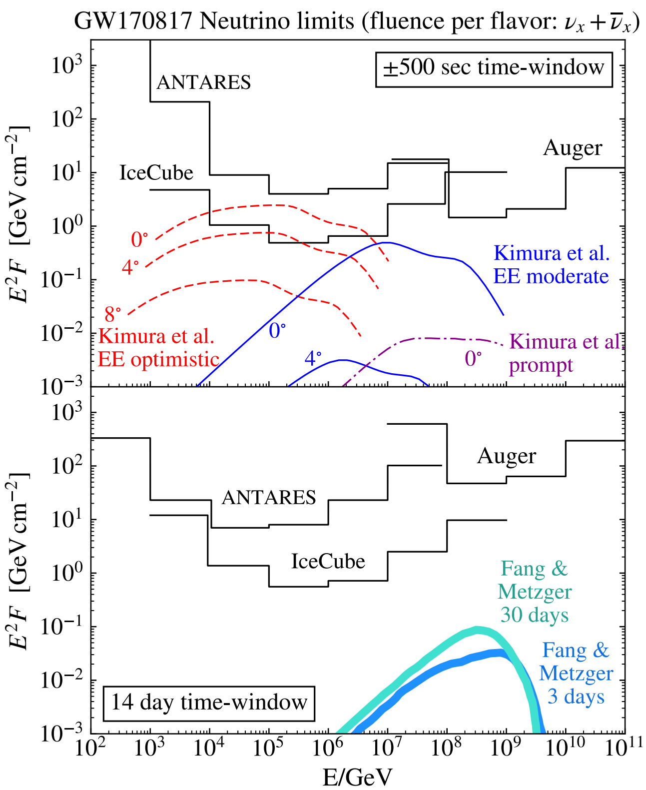


**Figure 2.** Upper limits (at 90% confidence level) on the neutrino spectral fluence from GW170817 during a ±500 s window centered on the GW trigger time (top panel), and a 14 day window following the GW trigger (bottom panel). For each experiment, limits are calculated separately for each energy decade, assuming a spectral fluence $F(E) = F_{\rm up} \times [E/\text{GeV}]^{-2}$ in that decade only. Also shown are predictions by neutrino emission models. In the upper plot, models from Kimura et al. (2017) for both extended emission (EE) and prompt emission are scaled to a distance of 40 Mpc and shown for the case of the on-axis viewing angle ($\theta_{\rm obs} \lesssim \theta_j$) and selected off-axis angles to indicate the dependence on this parameter. The shown off-axis angles are measured in excess of the jet opening half-angle $\theta_j$. GW data and the redshift of the host galaxy constrain the viewing angle to $\theta_{\rm obs} \in [0°, 36°]$ (see Section 3). In the lower plot, models from Fang & Metzger (2017) are scaled to a distance of 40 Mpc. All fluences are shown as the per the flavor sum of neutrino and antineutrino fluence, assuming equal fluence in all flavors, as expected for standard neutrino oscillation parameters.

100 PeV, the upper limit on an $E^{-2}$ power-law spectral fluence is $F(E) = 0.23 \times (E/\text{GeV})^{-2}\ \text{GeV}^{-1}\,\text{cm}^{-2}$.

The IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all photomultiplier signal rates. A neutrino burst signal from a galactic core-collapse supernova would be detected with high precision (Abbasi et al. 2011). The detector global dark rate is monitored continuously, the influence of cosmic-ray muons is removed, and low-level triggers are formed when deviations from the nominal rate exceed pre-defined levels. No alert was triggered during the ±500 s time window around the GW candidate. This is consistent with our expectations for cosmic events such as core-collapse supernovae or compact binary mergers that are significantly farther away than Galactic distances.

### 2.3. Pierre Auger Observatory

With the surface detector (SD) of the Pierre Auger Observatory in Malargüe, Argentina (Aab et al. 2015b), air showers induced by ultra-high-energy (UHE) neutrinos can be identified for energies above $\sim 10^{17}$ eV in the more numerous background of UHE cosmic rays (Aab et al. 2015a). The SD consists of 1660 water-Cherenkov stations spread over an area of $\sim 3000\ \text{km}^2$ following a triangular arrangement of 1.5 km grid spacing (Aab et al. 2015b). The signals produced by the passage of shower particles through the SD detectors are recorded as time traces in 25 ns intervals.

Cosmic rays interact shortly after entering the atmosphere and induce extensive air showers. For highly inclined directions their electromagnetic component gets absorbed due to the large grammage of atmosphere from the first interaction point to the ground. As a consequence, the shower front at ground level is dominated by muons that induce sharp time traces in the water-Cherenkov stations. On the contrary, showers induced by downward-going neutrinos at large zenith angles can start their development deep in the atmosphere producing traces that spread over longer times. These showers have a considerable fraction of electrons and photons that undergo more interactions than muons in the atmosphere, spreading more in time as they pass through the detector. This is also the case for Earth-skimming showers, mainly induced by tau neutrinos ($\nu_\tau$) that traverse horizontally below the Earth's crust, and interact near the exit point inducing a tau lepton that escapes the Earth and decays in flight in the atmosphere above the SD.

Dedicated and efficient selection criteria based on the different time profiles of the signals detected in showers created by hadronic and neutrino primaries, enable the search for Earth-skimming as well as downward-going neutrino-induced showers (Aab et al. 2015a). Deeply starting downward-going showers initiated by neutrinos of any flavor can be efficiently identified for zenith angles of $60° < \theta < 90°$ (Aab et al. 2015a). For the Earth-skimming channel typically only $\nu_\tau$-induced showers with zenith angles $90° < \theta < 95°$ can trigger the SD. This is the most sensitive channel to UHE neutrinos, mainly due to the larger grammage and higher density of the target (the Earth) where neutrinos are converted and where tau leptons can travel tens of kilometers (Aab et al. 2015a). The angular resolution of the Auger SD for inclined showers is better than 2°.5, improving significantly as the number of triggered stations increases (Bonifazi & Pierre Auger Collaboration 2009).

Auger performed a search for UHE neutrinos with its SD in a time window of ±500 s centered at the merger time of GW170817 (Abbott et al. 2017c), as well as in a 14 day period after it (Murase et al. 2009; Gao et al. 2013; Fang & Metzger 2017).

The sensitivity to UHE neutrinos in Auger is limited to large zenith angles, so that at each instant they can be efficiently detected only from a specific fraction of the sky (Abreu et al. 2012; Aab et al. 2016). Remarkably, the position of the optical counterpart in NGC 4993 (Abbott et al. 2017c; Coulter et al. 2017b, 2017a) is visible from Auger in the field of view of the Earth-skimming channel during the whole ±500 s window as shown in Figure 1. In this time period, the source of GW170817 transits from $\theta \sim 93°.3$ to $\theta \sim 90°.4$ as seen from the center of the array. The performance of the Auger SD array (regularly monitored every minute) is very stable in the ±500 s window around GW170817, with an average number of active stations amounting to $\sim 95.8 \pm 0.1\%$ of the 1660 stations of the SD array.

No inclined showers passing the Earth-skimming selection (neutrino candidates) were found in the time window $\pm 500$ s around the trigger time of GW170817. The estimated number of background events from cosmic rays in a 1000 s period is $\sim 6.3 \times 10^{-7}$ for the cuts applied in the Earth-skimming analysis (Aab et al. 2015a).

The absence of candidates in the $\pm 500$ s window allows us to constrain the fluence in UHE neutrinos from GW170817, assuming they are emitted steadily in this interval and with an $E^{-2}$ spectrum (Aab et al. 2016). Single-flavor differential limits to the spectral fluence are shown in Figure 2, in bins of one decade in energy. The sensitivity of the observatory is largest in the energy bin around $10^{18}$ eV. The single-flavor upper limit to the spectral fluence is $F(E) = 0.77(E/\mathrm{GeV})^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}$ over the energy range from $10^{17}$ eV to $2.5 \times 10^{19}$ eV.

In the 14 day search period, as the Earth rotates, the position of NGC 4993 transits through the field of view of the Earth-skimming and downward-going channels. As seen from the Pierre Auger Observatory, the zenith angle of the optical counterpart oscillates daily between $\theta \sim 11°$ and $\theta \sim 121°$. The source is visible in the Earth-skimming channel for $\sim$4% of the day and in the downward-going channel for $\sim$10.5% ($\sim$11.1%) in the zenith angle range $60° < \theta < 75°$ ($75° < \theta < 90°$). No neutrino candidates were identified in the two-week search period. Single-flavor differential limits to the spectral fluence are shown in Figure 2. The corresponding upper limit to the spectral fluence is $F(E) = 25\ (E/\mathrm{GeV})^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}$ over the same energy interval as for the $\pm 500$ s time window, where the difference is due to the relatively long periods of time when the source of GW170817 is not visible in the inclined directions.

## 3. Discussion

The nature of high-energy emission from the binary merger and its aftermath is not yet clear. We compared the expected spectral fluence for different emission scenarios to our observational upper limits to probe the properties of the merger and its aftermath. Here, we briefly outline the relevant information from electromagnetic observations and present our results for the different emission scenarios.

The merger occurred at a distance of $\sim$40 Mpc, which is the distance of its host galaxy NGC 4993, identified through electromagnetic observations (Abbott et al. 2017c; Coulter et al. 2017a, 2017b). The prompt gamma-ray emission from the source, GRB 170817A, had an observed isotropic-equivalent energy of $E_{\mathrm{iso}} \approx 4 \times 10^{46}$ erg, as recorded by *Fermi*-GBM (Abbott et al. 2017a). This is orders of magnitude below typical observed short GRB energies (Berger 2014; Abbott et al. 2017a).

Prompt gamma-ray emission in at least some short GRBs is followed by a weaker, extended emission that can last for hundreds of seconds (Norris & Bonnell 2006; Kimura et al. 2017). *Fermi*-GBM did not detect a temporally extended emission following GRB 170817A, placing a constraint of $\sim 2 \times 10^{46}\ \mathrm{erg\ s^{-1}}$ for a 10 s long emission period over 1 keV–10 MeV (Abbott et al. 2017a), significantly below typical luminosities observed for extended emission.

The very faint gamma-ray emission, along with its observed, delayed afterglow, are consistent with a typical short GRB viewed off-axis (Fong et al. 2017; Fraija et al. 2017; Granot et al. 2017; Haggard et al. 2017; Hallinan et al. 2017; Ioka & Nakamura 2017; Kim et al. 2017; Margutti et al. 2017; Murguia-Berthier et al. 2017; Troja et al. 2017). A GRB is viewed off-axis if its viewing angle $\theta_{\mathrm{obs}}$, defined as the angle between the jet axis and the line of sight, is greater than the jet opening half-angle $\theta_j$ (Granot et al. 2002). The viewing angle inferred from the data is $\theta_{\mathrm{obs}} \gtrsim 20°$, while typical opening half-angles for short GRBs are within $\theta_{\mathrm{j}} \approx 3°$–$10°$ (Berger 2014).

GW data combined with the measured redshift of the host galaxy further provide constraints on $\theta_{\mathrm{obs}}$. Here, we assume that the jet axis is aligned with the binary's total angular momentum vector. Adopting the Hubble constant from cosmic microwave background measurements by the Planck satellite (Ade et al. 2016), these data are consistent with $\theta_{\mathrm{obs}} = 0$, but also allow for a misalignment of $\theta_{\mathrm{obs}} \leqslant 28°$ at a 90% credible level. Adopting the Hubble constant from Type Ia supernova measurements (Riess et al. 2016) gives a similar result with maximum misalignment of $\theta_{\mathrm{obs}} \leqslant 36°$ at a 90% credible level (Abbott et al. 2017d).

Considering this off-axis scenario, we examined the expected high-energy neutrino emission from a typical GRB observed at different viewing angles. The most promising neutrino-production mechanism from GRBs is related to the extended gamma emission, due to its relatively low Lorentz factor resulting in high meson production efficiency (Kimura et al. 2017). In Figure 2, we compared our observational constraints with the expected neutrino fluence from the GRB's extended emission. For the on-axis (i.e., $\theta_{\mathrm{obs}} \lesssim \theta_j$) spectral fluence $F_{\mathrm{on}}$, we assumed the results of Kimura et al. (2017), rescaled to 40 Mpc. We approximated the observed off-axis spectral fluence, $F_{\mathrm{off}}(E)$, for these models using $F_{\mathrm{off}}(E) = \eta F_{\mathrm{on}}(E/\eta)$, where the scaling factor $\eta = \delta(\theta_{\mathrm{obs}})/\delta(0)$ accounts for different Doppler factors $\delta(\theta_{\mathrm{obs}}) = [\Gamma(1 - \beta\cos(\theta_{\mathrm{obs}} - \theta_j))]^{-1}$ (Granot et al. 2002).

For comparison, we also examined the expected neutrino flux associated with the prompt GRB emission (e.g., Moharana et al. 2016; Kimura et al. 2017). This emission phase is less favorable for neutrino production than the extended emission. We see in Figure 2 that prompt emission from a single merger event is unlikely to produce a detected neutrino for the considered observatories, even if viewed on-axis.

Another proposed explanation for the faintness of gamma-ray emission is the interaction of the GRB jet with ejecta material from the merger (Gottlieb et al. 2017; Kasliwal et al. 2017; Piro & Kollmeier 2017). Energy deposition by the jet into the neutron star ejecta can form a cocoon that expands outwards at mildly relativistic speeds over a wide opening angle. Faint gamma-ray emission is then expected during the breakout of this cocoon from the outer tail of the ejecta (Gottlieb et al. 2017).

High-energy neutrino production in this scenario may significantly exceed the observed gamma-ray emission as neutrinos can escape through the ejecta even before it becomes transparent to gamma-rays. This scenario resembles that of a jet burrowing through the stellar envelope in a core-collapse event (Mészáros and Waxman 2001; Razzaque et al. 2003; Bartos et al. 2012; Murase & Ioka 2013). Nevertheless, if the observed gamma-rays come from the outbreak of a wide cocoon, it is less likely that the relativistic jet, which is more narrowly beamed than the cocoon outbreak, also pointed toward Earth.

We further considered an additional neutrino-production mechanism related to ejecta material from the merger. If a rapidly rotating neutron star forms in the merger and does not immediately collapse into a black hole, it can power a relativistic wind with its rotational energy, which may be responsible for the sometimes observed extended emission

(Metzger et al. 2008). Optically thick ejecta from the merger can attenuate the gamma-ray flux, while allowing the escape of high-energy neutrinos. Additionally, it may trap some of the wind energy until it expands and becomes transparent. This process can convert some of the wind energy to high-energy particles, producing a *long-term* neutrino radiation that can last for days (Murase et al. 2009; Gao et al. 2013; Fang & Metzger 2017). The properties of ejecta material around the merger can be characterized from its kilonova/macronova emission.

Considering the possibility that the relative weakness of gamma-ray emission from GRB 170817A may be partly due to attenuation by the ejecta, we compared our neutrino constraints to neutrino emission expected for typical GRB parameters. For the prompt and extended emissions, we used the results of Kimura et al. (2017) and compared these to our constraints for the relevant $\pm500$ s time window. For extended emission we considered source parameters corresponding to both optimistic and moderate scenarios in Table 1 of Kimura et al. (2017). For emission on even longer timescales, we compared our constraints for the 14 day time window with the relevant results of Fang & Metzger (2017), namely, emission from approximately 0.3 to 3 days and from 3 to 30 days following the merger. Predictions based on fiducial emission models and neutrino constraints are shown in Figure 2. We found that our limits would constrain the optimistic extended-emission scenario for a typical GRB at $\sim$40 Mpc, viewed at zero viewing angle.

## 4. Conclusion

We searched for high-energy neutrinos from the first binary neutron star merger detected through GWs, GW170817, in the energy band of [$\sim10^{11}$ eV, $\sim10^{20}$ eV] using the ANTARES, IceCube, and Pierre Auger Observatories, as well as for MeV neutrinos with IceCube. This marks an unprecedented joint effort of experiments sensitive to high-energy neutrinos. We have observed no significant neutrino counterpart within a $\pm500$ s window, nor in the subsequent 14 days. The three detectors complement each other in the energy bands in which they are most sensitive (see Figure 2).

This non-detection is consistent with our expectations from a typical GRB observed off-axis, or with a low-luminosity GRB. Optimistic scenarios for on-axis gamma-attenuated emission are constrained by the present non-detection.

While the location of this source was nearly ideal for Auger, it was well above the horizon for IceCube and ANTARES for prompt observations. This limited the sensitivity of the latter two detectors, particularly below $\sim$100 TeV. For source locations near, or below the horizon, a factor of $\sim$10 increase in fluence sensitivity to prompt emission from an $E^{-2}$ neutrino spectrum is expected.

With the discovery of a nearby binary neutron star merger, the ongoing enhancement of detector sensitivity (Abbott et al. 2016) and the growing network of GW detectors (Iyer et al. 2011; Aso et al. 2013), we can expect that several binary neutron star mergers will be observed in the near future. Not only will this allow stacking analyses of neutrino emission, but it will also bring about sources with favorable orientation and direction.

The ANTARES, IceCube, and Pierre Auger Collaborations are planning to continue the rapid search for neutrino candidates from identified GW sources. A coincident neutrino, with a typical position uncertainty of $\sim$1 deg$^2$ could significantly improve the fast localization of joint events compared to the GW-only case. In addition, the first joint GW and high-energy neutrino discovery might thereby be known to the wider astronomy community within minutes after the event, opening a rich field of multi-messenger astronomy with particle, electromagnetic, and gravitational waves combined.

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